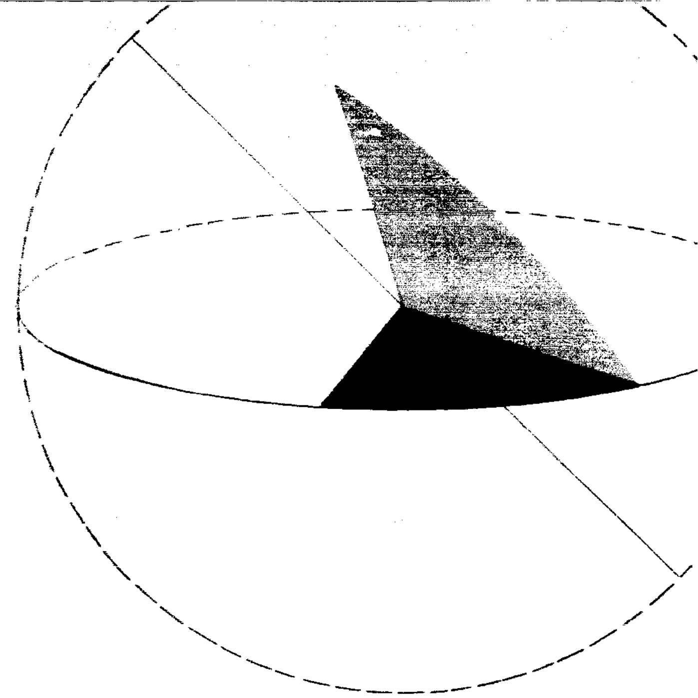

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LUMINESCENCE OF THE LUNAR SURFACE AND THE INTENSITY OF THE SOLAR CORPUSCULAR RADIATION 1956

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LUMINESCENCE OF THE LUNAR SURFACE AND THE INTENSITY OF THE SOLAR CORPUSCULAR RADIATION
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by

N. A. Kozyrev

Translated by J. L. Zygielbaum

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JET PROPULSION LABORATORY
A Research Facility of
National Aeronautics and Space Administration
Operated by
California Institute of Technology
Pasadena, California
January 15, 1961

TABLE

FIGURES

LUMINESCENCE OF THE LUNAR SURFACE AND THE INTENSITY OF THE SOLAR CORPUSCULAR RADIATION

by

N. A. Kozyrev

(Per Akademya Nauk SSSR Izvestia Krymskoi Astrofizitcheskoy Observatorye)
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The quantitative investigation of the luminescence of the lunar surface was accomplished by comparing the contours of broad Fraunhofer lines in the spectra of lunar details, with the contours of these lines in the solar spectrum. We succeeded in establishing and measuring the luminescence of the system Aristarchus-Herodotus. The luminous properties have proven to be associated with the white matter in the ray system of the lunar surface. Other investigations of details of the lunar surface have not disclosed any luminescence. These measurements, together with measurements of the spectral refractive capability of the crater Aristarchus, have made it possible to find a luminescence curve depending on the wave line. There obviously exist two belts: a brighter ultraviolet with a maximum of about 3900 Å and a blue belt (less reliably determined) with a maximum of about 4300 Å.

The luminescence of the Aristarchus crater is stronger after a full Moon. On October 4, 1955, a particularly strong luminescence, which exceeded the normal by 4 times, was observed. This increase of luminescence was explained by the activity of a corpuscular flux from the Sun on the surface of the crater. From this was determined the concentration of protons in the flux near the Moon, which proved to be equal 5×10^3 particles per cm^2. These observations, in the absence of luminescence on the dark side of the lunar surface, indicate that the Moon has no magnetic field. Assumptions on the nature of the lunar system are described.

The crepuscular phenomena on the Moon were not discovered even during very thorough investigations. Lyot and Dollfus have, by their observations on a coronograph, increased the upper limits of a possible lunar atmosphere, establishing this atmosphere at 3×10^{-8} of the Earth's atmosphere (Ref 1). However, this upper boundary did not exclude the possibility of the existence of an ionosphere on the Moon and the phenomena connected with it; for instance, the illumination of the lunar night sky. From this view point, the study of the spectrum of the dark rim on the lunar disk near a new Moon is of great interest.

This type of spectrogram was obtained through the 50-inch reflector of the Crimean Observatory during a perpendicular position of the spectrograph's aperture toward the rim of the lunar disk. Spectrographs were obtained with a camera equipped for a luminosity of 1:4 during an exposure of about 1 hour. Since the brightness of the atmospheric luminosity of the Moon near the rim should be many times greater than over the disk, then the luminosity of the lunar sky (which is approximate to the luminosity brightness of the sky of the Earth) should have been noticeable on our pictures. In a photograph, the spectrum of a dim light would be separated from a weaker spectrum of the sky background; however, no peculiarities in the spectrum of the sky near the lunar rim were discovered.

Thus, there is practically no ionosphere on the Moon. The stable solar radiation, then, should fall directly on the surface of the Moon and cause a luminescence of minerals which compose its surface. On Earth the corpuscular solar radiation causes the aurora borealis, which is a cathode luminescence of the ionosphere. On the Moon the polar luminescence should take place directly on the surface of the planet. At low temperatures (on the order of -160°C) on the dark side of the Moon, many minerals become luminescent with noticeable coefficients of energy admission. Therefore, against the background of the ash light, the polar luminescence of the lunar surface should have been observed very clearly. Such phenomena were never observed on the Moon; therefore, a positive conclusion follows regarding the absence of a magnetic field on the Moon. In the absence of a magnetic field, the corpuscular solar radiation should fall on the lunar surface together with protons, by the same geometrical laws. Consequently, the lunar luminescence can be observed only on the side illuminated by the Sun.

Link (Ref 2) has for the first time discovered the following signs of luminescence of the lunar surface:

(1) A great relative brightness of certain details on the lunar surface during its eclipse which, following from the photometrical measurements of these details during solar illumination, can be explained by a luminescent afterglow of considerable duration.

(2) The correlation of the lunar brightness with possible oscillations of the solar constant. Oscillations of the lunar brightness can be considerable due to the changes in the stable solar radiation, which, with the aid of the luminescent glow, is added to the solar light that is reflected by the Moon and is visible in the spectral regions. These symptoms are indirect, and therefore direct spectrophotometrical proof on the luminescence of the lunar surface is required.

A photometric comparison of the continuous spectrum of the lunar surface with the spectrum of the Sun can definitely indicate luminescence only when the superposed spectrum of luminescence contains separate narrow lines. Usually the spectrum of mineral luminescence consists of broad belts, the accumulation of which (with the reflection of the solar spectrum) can not be, with assurance, separated from the specific spectral curve of refraction of the lunar surface. However, with complete definiteness and on the basis of accurate measurements, luminescence can be discovered from a comparison of the contours of the Fraunhofer lines in the spectra of the Moon and the Sun.

We will define by $I_{\odot}$ the intensity of the solar spectrum inside the Fraunhofer line in relation to the continuous spectrum. It is obvious that in the absence of luminescence, the lines of the lunar spectrum cannot undergo any changes, and the same values $I_{\odot}$ should be obtained in the lunar spectrum. Let us assume that there exists a luminescence with a brightness of x in relation to the continuous spectrum of refraction of lunar light. The brightness x will be considered as a constant for the entire Fraunhofer line. In order to obtain the contour of the line in the lunar spectrum $I_{☾}$, we should add to $I_{\odot}$ the luminescence of brightness x:

$$I_{☾} = (I_{\odot} + x)k$$

where k is a certain coefficient of proportion, the magnitude of which is determined by the condition of intensity in the continuous spectrum--$I_{☾} = I_{\odot} = 1$. Thus

$$I_{☾} = \frac{I_{\odot} + x}{1 + x} \tag{1}$$

from which we will obtain the possibility to determine x by comparing the contours of the lines in the lunar and the solar spectra:

$$x = \frac{I_{☾} - I_{\odot}}{1 - I_{☾}} \tag{2}$$

From Formula 2 it is obvious, that various brightness values of the corresponding points in the lunar and solar spectra ($I_{☾} - I_{\odot}$) are proportional ($1 - I_{☾}$). Consequently, the most variable contours should be observed in the center of the line and the smallest at the edges. The final intensity of the lines, due to the luminescence, will be large and the semi-width will be small; as a result the line will seem to be narrower than in the solar spectrum. Within a moderate limit, one should restrict the investigation of contours only to especially broad Fraunhofer lines in order to avoid instrumental and photometric errors. On the other hand, by the same brightness of luminous glow, the value x should be larger than in the violet part of the spectrum, where a considerable decrease takes place in the brightness of the solar spectrum and in the reflective capabilities of the lunar surface. Therefore, a search for luminous glow should naturally begin from the investigation of the contours of the lines H and K of ionized calcium.

We obtained spectrographs of various regions of the lunar surface in the fall of 1955 with the 50 inch reflector of the Crimean Observatory, with the help of a spectrograph utilizing a large camera which yielded a linear dispersion of about 15 Å/mm near the doublet H and K. With an aperture width of 0.05 mm and Ilford hypo-panchromatic film, three exposures were made on the order of 2 to 10 minutes for the visible sector of the spectrum, and 30 to 40 minutes for the contours H and K.

Whenever it was possible, during the days of observation, the spectrum of the Sun was taken for comparison with the same instruments and the same film. During the solar observations the large mirror of the reflector was covered with a diaphragm which contained 20 openings with a diameter of 4 mm each, which were uniformly distributed along the surface of the mirror. Photographs of the Sun were obtained by various exposures from 0.2 to 10 seconds, and the photometric scale was obtained with an exposure of about 5 to 10 minutes.

Having a collection of these solar spectra, it was possible to compare visually the form of lines in the spectra of the Moon and the Sun by similar densities of a continuous spectrum. Such a possibility has simplified very much the search of luminous regions on the lunar surface. Investigations were made of the surfaces of the lunar seas (the Sea of Brightness and the Sea of Rains), the mountainous part of the central region of the Moon, the bottom of certain craters (Plato, Schickard, Copernicus), and the Wood spot. These investigations gave a negative result. The contours of the lines H and K have proven to be similar to the solar spectrum. Only the crater Aristarchus with the adjacent Herodotus crater (taken as examples of the ray system) have undoubtedly shown a different contour of these lines. In the spectrum of Aristarchus, the central part of the lines H and K seem to be considerably narrower than in the solar spectrum.

The crater Aristarchus is located in the eastern part of the lunar disk and has the following selenographic coordinates: $\phi = +23.0$ deg, $\lambda = -47.1$ deg. The angle of reflection ϵ (that is, the angle between the ray of vision and the normal towards the surface of the crater) is approximately 46 degrees. The ray system of the craters Aristarchus-Herodotus represent a broad illuminated halo without separate long rays and, therefore, are very convenient for spectral investigations.

Figure 1 gives a comparison of the contours of the line H (3968.6 Å) of the Ca^+ spectra of Aristarchus on October 4, 1955, and the Sun. In order to decrease the error of the characteristic curve, these contours were obtained with negatives of the same density as the continuous spectrum. The constructive contour in the solar spectrum agreed well with the contour of the corresponding line in the photometric atlas of Mennaert.

The great variety of contours of lines obtained in the spectra of Aristarque and the Sun are illustrated in Figure 2 in which the intensity of the lines in the solar spectrum $I_{\odot}$ are projected along the abscissa and the intensity in the spectrum of Aristarchus $I_{☾}$ is layed out along the ordinate axis, at the same distances from the center of the lines. In accordance with Formula 1, a linear dependence of $I_{☾}$ from $I_{\odot}$ should be obtained in the case of luminescence. This straight line should cut off on the ordinate axis ($I_{\odot} = 0$) a segment $I_{☾} = \frac{x}{1 + x}$. Thus it is possible, by means of this graph, to find at once the percentage of luminescence in relation to the intensity of the constant spectrum which is reflected by Aristarchus: $x = 13\%$.

The points in Figure 2 are projected sufficiently well along the line, with the exception of the point which is located closest to the beginning of the coordinate, which represents the remaining intensity of the line H. It is essential that during the measurement of other contours similar results should be obtained; luminescence will increase the residual intensity of the deep line considerably less than would appear along other points of that same contour. It is obvious that this is due to a certain systematical error which is most likely related to the Eberhard effect. Actually the background density near the strong darkening is always less than the normal value on a film. Thanks to the luminescence, the line contours become narrow (Fig 1), and this effect should appear with greater force than in the solar spectrum. As a result, the density in the center of the line will be increased by the luminescence less than necessary.

The results of measurements of the luminescence of the Aristarchus crater on different days is given in Table 1. In this table α is the angle of the lunar phase (which is positive after a full Moon), i is the angle of solar rays (or the zenith distance of the Sun in the case of the Aristarchus at the moment of observations), x_H is the luminosity percentage measured along the contours of the line H (3968.6 Å), x_K is the luminescence percentage along the contours of the line K (3933.8 Å).

Table 1 shows that before a full Moon Aristarchus has a lower luminescence than after a full Moon, when $\alpha > 0$ deg. On September 28 Aristarchus was near the terminator with no difference in color from the adjacent parts of the lunar surface, and no signs of luminescence were discovered. During a somewhat larger phase angle on October 28, a light coloring appeared, which is characteristic for ray systems, and at the same time the luminescence of the crater returned.

"Luminophore" is obviously a shining matter of the ray system, which is located on the bottom of small depressions in the crater. In Figure 3 is presented a probable diagram of the distribution of light matter of the rays in relation to the view line and direction of solar rays. In this diagram, it can be seen that near the terminator the microrelief of the surface should cover the luminescent matter and that the days which follow a full Moon should be the most favorable for observations of luminescence, since the solar rays fall almost perpendicularly to the surface of the crater.

Another interesting circumstance is the fact that the luminescence, which is determined along the line K, is 1-1/2 times larger than along the line H. It is obvious that the doublet H and K are on the border of the luminescence line, the intensity of which increases towards the ultraviolet side of the spectrum. Therefore, knowing the luminescence for the wavelengths H and K, it is possible to try to find the full contour of the luminosity belt, according to the distribution of energy in the uninterrupted spectrum of Aristarchus.

In Figure 4 are presented the results of measurements on energy distribution in the spectrum of Aristarchus in relation to the spectrum of the Sun. Along the ordinate axis is projected the logarithm of the brightness relation in the spectrum of Aristarchus to the brightness of the spectrum of the Sun for the same wavelengths. The constructed curves represent the spectral reflection capability of Aristarchus for two observations before a full Moon and two after a full Moon. The null point of these curves is entirely arbitrary along the vertical. The uppermost curve gives a relative distribution in the spectrum of Aristarchus near the terminator, when the ray system was not visible. The lower curve shows more white (that is, the neutral) refraction by the ray halo and corresponds to observations after a full Moon.

Data in Table 1 make it possible to notice (little crosses in Fig 4) the intensity of the uninterrupted light spectrum reflected by the Moon without luminescence for the wavelengths H and K. By these little crosses, it is possible to outline (broken line) the probable path of the spectral curve without luminescence. As a result, it becomes possible to define x as a function of the wavelength. It is always possible that the rays of the curves near the belt G (4308 Å) are also affected by luminescence. As a result of the low depth of the belt G, it is difficult to make a reliable determination of x along its contours. However, one can notice that the depth of the belt G in the spectrum of Aristarchus is less than in the solar spectrum. This circumstance confirms the reality of the second blue belt of luminescence with a maximum of about 4300 Å.

We will try now to pass from the relative values $x(\lambda)$ which characterize luminescence, to the absolute energy values. We will define by L_λ the absolute value of intensity of luminosity of light which is reflected from the lunar surface by a phase angle of observations. Then

$$L_\lambda = x(\lambda) B_\lambda \tag{3}$$

By the reflective capability of the lunar surface, we will understand the expression

$$A_\lambda = \frac{\pi B_\lambda}{S_\lambda} \tag{4}$$

where S_λ is the intensity of the solar radiation at the distance from the Moon to the Sun. S_λ might be expressed by a mean intensity of radiation of the solar surface F_λ:

$$S_\lambda = 2.16 \times 10^{-5} \pi F_\lambda \tag{5}$$

For a full energy of luminescent glow from an area-unit/sec in a single interval of wavelengths, we obtained the expression

$$\pi L_\lambda = A(\lambda)x(\lambda) \times 2.16 \times 10^{-5}\ \pi F_\lambda$$

Utilizing the values of F_λ according to the measurements of Abbot, which were processed by Minnaert (Ref 3), it is possible to calculate the magnitude

$$\pi L_\lambda / A_\lambda = x(\lambda) \times 2.16 \times 10^{5}\ \pi F_\lambda \tag{6}$$

The results of these calculations, which were made for the case of the greatest luminescence (October 4; lower curve in Fig 4), are presented in Figure 5. As can be seen from Figure 4, the reflective capability $A(\lambda)$ for this phase (in the section of the spectrum which is of interest to us) does not depend on the wavelength: $A(\lambda) = A =$ constant. Thus, the curve in Figure 5 reproduces the luminescence as a function of wavelength. The broken line indicates the probable extrapolation of this curve for the shortwave part of the spectrum. The values πL_λ in Figure 5 pertain to an interval of wavelengths which equal 100 Å; that is, to a unit of the horizontal scale. Thus, in order to calculate the entire energy of luminescence, it is sufficient to determine the area of this curve and to multiply it by 10^3. We will obtain

$$\int_0^\infty \pi L_\lambda d\lambda = 1.6 \times 10^4 \times A \text{ erg/cm}^2 \text{ sec} \tag{7}$$

The energy of high solar radiation E, which caused the luminescence of the Aristarchus crater on October 4, 1955, can be determined from the expression in Equation 7 by introducing the coefficient of energy output of luminescence Q of our substance. We will define by n the portion of area which is taken up by the light luminescent substance on the visible surface of the crater. Then

$$E = \frac{A}{nQ} \times 1.6 \times 10^4 \text{ erg/cm}^2 \text{ sec} \tag{8}$$

Thus, the energy which creates luminescence is always of considerable magnitude, on the order of 1 percent of the solar constant ($S = 1.32 \times 10^6$).

Data from Table 1 show that on October 4 an abnormality of high luminescence was observed. Actually one month later (November 4) under similar conditions (that is, approximate values of α and i) the luminescence proved to be 4 times weaker. This luminosity is most probably normal, since it coincides with the preceding observations of October 28. One might consider that the normal luminosity exists constantly and is aroused by an energy 4 times less than the indicated value of Equation 8. The source of this luminescence might be the nearby ultraviolet solar radiation: $\lambda < 3000$ Å. However, this ultraviolet radiation of the Sun corresponds to a temperature of a rotating layer (4800°C) and cannot experience noticeable oscillations. Therefore, the abnormal flare-up of luminescence should be caused by other agents.

The source of hard ultraviolet and X-rays from the Sun is the solar corona. The flux of this radiation depends basically on the concentration of electron gas in the corona and can, therefore, be calculated with sufficient reliability. As was proven by the investigations of I. S. Shklovsky, this flux represents only a fraction of 1 erg (Ref 4) at the Earth distance, and is entirely insufficient to cause luminescence. The ultraviolet radiation of the chromosphere within the lines should be considerably larger, but even that is not sufficient to explain the absorbed luminescence.

It remains to consider that the luminescence is created by the corpuscular flux of the Sun. Let us compute the number of particles--protons $n_p/1$ cc--in a corpuscular flux. The flux of particles transfers an energy of

$$E = \frac{m_p v^2}{2} n_p v \tag{9}$$

where v = 1500 km/sec, and $m_p = 1.7 \times 10^{-23}$. Comparing the expressions of Equation 8 and Equation 9 we find

$$n_p = \frac{3.2 \times 10^4}{mpv^3} \frac{A}{nQ} = \frac{A}{nQ} \times 5 \times 10^3 \text{ cm}^{-3} \tag{10}$$

The absolute value of reflection capability of Aristarchus, which is determined by the expression in Equation 4, was obtained by A. V. Markov (Ref 5) for the visible region of the spectrum (λ = 5500 Å): near a full Moon A_V = 0.20. In the case of a phase angle of about 40 to 50 degrees this value should be 2 times smaller. It is obvious from the curves in Figure 4 that the reflection capability of the surface of Aristarchus in the ultraviolet part of the spectrum should be less than the former by a factor of 2. We obtain: A = 0.05.

It is considerably more difficult to evaluate the value of the coefficient of the useful effect of Q. In the case of photoluminescence, Q is usually great and might approach 1 unit. In our case which is analogous to cathode luminescence, Q should be considerably less. The luminescent substance of the Aristarchus crater is essentially lighter than other substances of the lunar surface. Therefore, even during perpendicular solar rays, it barely heats to positive temperatures. This circumstance enables the increase of Q. Therefore, it is possible to assume that Q ≅ 0.1.

Considering further that n is on the order of 1/2, we find: $A/nQ \cong 1.0$. Consequently,

$$n_p \cong 5 \times 10^3 \text{ cm}^{-3}. \tag{11}$$

Our evaluation of the density of corpuscular discharge from the Sun is in correspondence with the evaluation of other authors who arrived at these results with entirely different methods. Back in 1929, Chapman and Ferraro (Ref 6) found that a moderate magnetic storm is created by a corpuscular flux with a density of $n \cong 10^3 \text{ cm}^{-3}$. S. K. Vsechvyatsky, who considers the corona rays as corpuscular solar fluxes, obtained the same value for the density of fluxes on the order of 10^3 cm^{-3} (Ref 7).

Final verification of the explanation that lunar luminescence is due to corpuscular radiation of the Sun should be obtained by a comparison of the intensity of luminescence with the intensity of the Aurora Borealis and magnetic storms on the Earth. We think that a systematical observation of the luminescence of the Aristarchus crater and other similar formations of the lunar surface might yield much valuable information on the corpuscular radiation of the Sun. The surface of the Aristarchus crater is a natural luminating screen, beyond the realms of the Earth's atmosphere and entirely free of the effects of the magnetic field. The considerable width (more than 10 Å) of the line H and K might make it possible to conduct systematical observations of luminescence with very moderate means. It seems to be easy to realize an instrument which would register systematically the intensity of luminescence.

A few words should be said about the possible nature of the luminating substance of Aristarchus. Unfortunately, the distribution of energy in the spectrum of luminescence (Fig 5) cannot lead to a reliable determination of the "luminophore". The point is that negligible mineral admixtures might considerably change the shape of this energy curve. It should be emphasized that this substance does not contain even the most negligible admixture of iron, since iron is a very active damping agent of luminescence.

Obviously, there is a light luminating substance of the ray systems on the Moon, which fills up the crevices near the craters and is, according to A. V. Khabakov (Ref 8), the youngest formation of the lunar surface. This substance should be almost white with considerable albedo. Since in the case of Aristarchus the average albedo during a full Moon is $A_V = 0.20$, the visible albedo of the "luminophore" when $n = 1/2$ should be around 0.30 to 0.40; that is, on the order of albedo of white sand. Small indetectable crevices, which contain this substance, could have been created along radial directions under the influence of forces originating from the center of the crater of the given ray system. Gases and solutions might have been discharged through these craters forming a white luminescent substance. Therefore, it is very possible that the substance of ray systems is a certain variety of quartz. In time this substance should probably be covered with meteoric, nonluminescent dust which falls continuously on the surface of the Moon. This probably explains the complete absence of ray systems near craters of an ancient formation.

Obviously, one might consider that the general mass of meteoric dust with dimensions of less than 2 to 3μ, which falls on the entire surface of the Earth and amounts to about 1 ton/day. Thus, during one year the Earth is covered with about 10^8 cc of that dust. The surface of the Earth has an area of about 5 x 10^{18} cm^2. Consequently, over a period of 5 x 10^{10} years, this dust should cover the surface with a layer of 1 cm thick. A noticeable cover of the mentioned dust should be present in 50,000,000 years. From this, it follows that the last mountain-forming period in the life of the Moon took place not earlier than 50,000,000 years ago.

Table 1

GMT (1955), hr:min	α, deg	i, deg	x_H, %	x_K, %	x_K/x_H
Sept. 28, 18:0	-38.5	88	0.0	0.0	-
Oct. 28, 18:30	-35.6	85	2.2 ± 0.2	3.3 ± 0.5	1.5
Oct. 4, 22:00	+41.4	23	13.0 ± 1.0	19.0 ± 1.0	1.5
Nov. 4, 22:00	+63.8	31	3.0 ± 0.3	4.2 ± 0.3	1.4

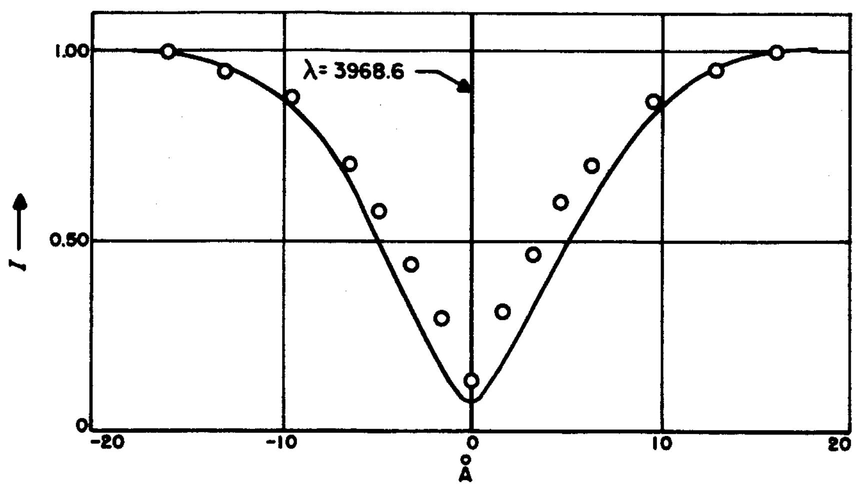

Fig. 1. Comparison of contours of line H (3968.6 Å) in the spectra of the crater Aristarchus on October 4, 1955 (circles), and the Sun (solid line)

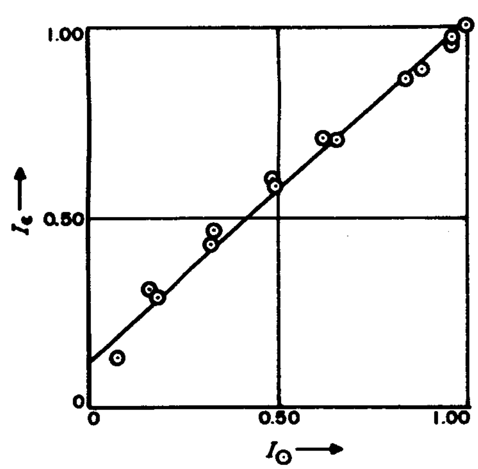

Fig. 2. Comparison of intensity of H line (3968.6 Å) in spectra of Aristarchus crater on October 4, 1955-- $I_☾$ and the Sun $I_\odot$

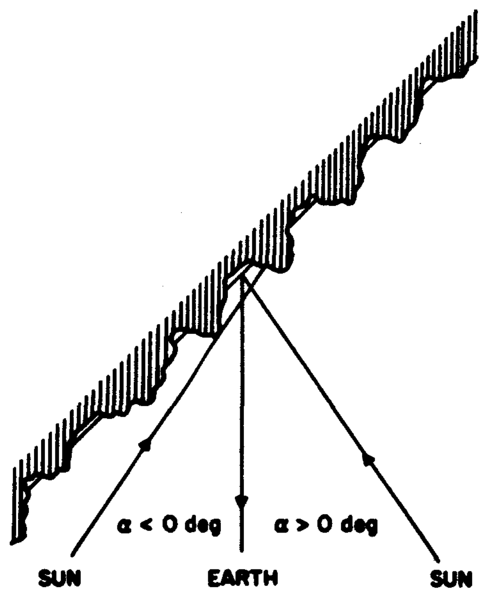

Fig. 3. Diagram of surface illumination of the Aristarchus crater, before and after a full Moon. Shaded area indicates formations on lunar surface. Absence of shade indicates luminescent matter

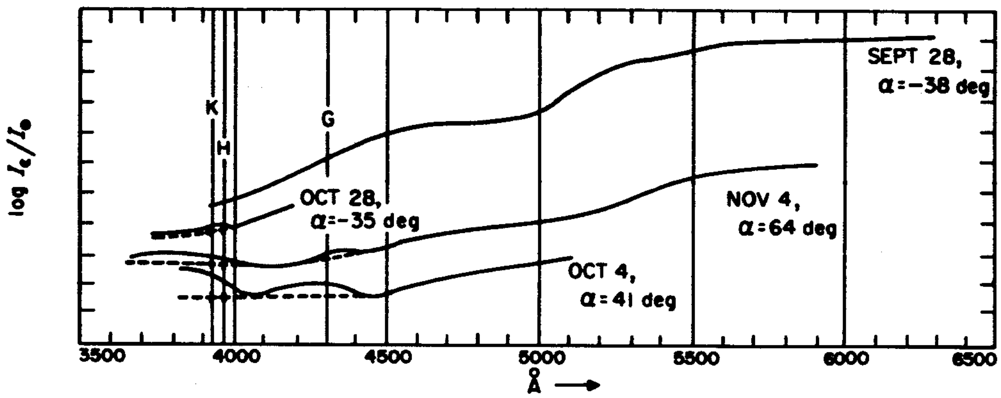

Fig. 4. Curves of spectral reflection capability of the Aristarchus crater: log ($I_☾$ /$I_☉$). One graduation on the vertical axis equals 1/10 of a decimal logarithm in the spectrum of the crater to the brightness in the spectrum of the Sun. The null point of the curves is arbitrary

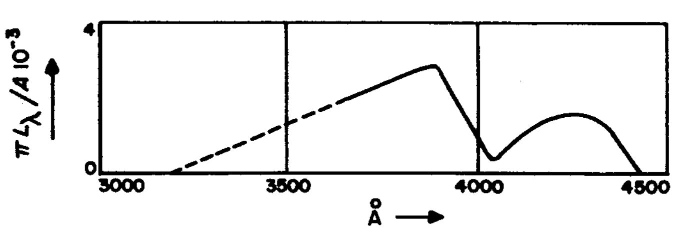

Fig. 5. Spectral curve of luminescence of the crater Aristarchus on October 4, 1955

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